Simulations of binary coalescence of a neutron star and a black hole

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ABSTRACT

We present the results of Newtonian hydrodynamic simulations of the coalescence of a binary consisting of a black hole with a neutron star. The calculations show that for a wide range of initial conditions the core of the neutron star survives the initial mass transfer episode. We therefore identify black hole–neutron star binaries as the astrophysical production site of low mass neutron stars unstable to explosion. The relevance of the simulations to the theory of gamma–ray bursts is also discussed.

Subject headings: gamma rays: bursts — binaries: close — stars: neutron — hydrodynamics

1. Introduction

The ultimate fate of a close binary composed of a neutron star and a black hole has first been discussed (Wheeler 1971) shortly after the discovery of neutron stars. It has been pointed out that the coalescence of such a binary would make a promising site for the r–process nucleosynthesis (Lattimer & Schramm 1976); the same authors already suggested that the coalescence may give rise to a gamma–ray burst (GRB), but the correctly estimated event rate was thought to be too low in the then prevailing paradigm of Galactic sources for GRBs. As discussed in the next section, recent observations led to a revived interest in black hole–neutron star binaries as sources of GRBs.

A seemingly separate problem is that of the fate of a neutron star with mass below the stability limit (e.g. Page 1982, Sumiyoshi *et al.* 1997). It has been though that such stars will undergo a violent explosion but no reliable production sites had been identified.

In this Letter we report on our Newtonian simulations of the final stages of evolution of a black hole–neutron star binary. Surprisingly, our results suggest a possible unification of the disparate paths of investigation mentioned above.

2. Black hole–neutron star coalescence as a potential source of GRBs

The properties of dim optical transients (van Paradijs *et al.* 1997, Djorgovski *et al.* 1997, Metzger *et al.* 1997) associated with gamma-ray bursts (GRBs) reinforce the view (Paczyński 1991, Meegan *et al.* 1992), hitherto held on statistical grounds, that the sources of the observed GRBs are not located in the Galaxy or the nearby clusters of galaxies. All facts are consistent with a "cosmological" origin of GRBs (Fishman & Meegan 1995). In fact, the isotropy of GRBs and the distribution of their peak flux favour a typical distance between $\sim 100\,\mathrm{Mpc}$ and $\sim 1\,\mathrm{Gpc}$ to the closest sources of the observed GRBs. The reported redshift (Metzger *et al.* 1997) of $z = 0.8$ to the optical counterpart of GRB970508 should settle the issue of the intrinsic luminosity of the GRB sources. A distance of $\sim 1\,\mathrm{Gpc}$ implies that up to 10^{51} ergs must be released in gamma rays to account for the observed fluences of $\sim 10^{-7.5}$ to $\sim 10^{-3}\mathrm{erg/cm}^2$. All models (Colgate 1968, Paczyński 1986, Eichler, Livio, Piran & Schramm 1988, Paczyński 1991, Usov 1992, Mészáros & Rees 1992, Woosley 1993) involve the birth or death of a neutron star or a star like it.

To be efficiently converted to observed gamma rays, the energy released in the primary event must have a line of sight to the observer which is sufficiently baryon-free to allow a relativistic blast wave (Paczyński 1986, Mészáros & Rees 1992, Mészáros & Rees 1993) to expand at velocities close to the speed of light. It has been argued (Mészáros, Laguna & Rees 1993) that the interaction of such relativistic outflow with the interstellar medium will result in shock acceleration of electrons and amplification of magnetic fields yielding significant emission of gamma-rays rays through synchrotron radiation. The expected afterglow (Vietri 1997) may be consistent with the X-ray and optical transients detected by the Beppo-SAX satellite and follow-up observations (van Paradijs *et al.* 1997). We are looking, then, for a process which would release a sufficient amount of energy in a baryon-free direction, and one whose characteristic timescales correspond to the variability and durations of the observed GRBs (in the shocked fireball model the GRB timescales must arise at the source (Piran 1997)).

A sufficiently small baryon loading of the plasma is obtained (Haensel, Paczyński & Amsterdamski 1991) in a natural way in the mergers of two strange stars, because the strange-quark matter making up their bulk is self-bound and hence immune to lofting by radiation. But the disruption of a strange star would pollute the Galactic environment with strange-quark nuggets which would preclude (Caldwell & Friedman 1991) the further formation of young pulsars (neutron stars). Thus, the merger of a strange star with anything else is excluded as a source of GRBs (Kluźniak 1994).

The most conservative scenario of GRB formation involves the coalescence of a binary system composed of two neutron stars (Paczyński 1986, Eichler, Livio, Piran & Schramm

1988). These events are certain to occcur and a satisfactory lower limit to their rate can reliably be inferred (Lattimer & Schramm 1976, Narayan, Piran & Shemi 1991), e.g. from the statistics of the known Hulse-Taylor type neutron star binaries. There is disagreement as to the outcome of the last stages of evolution of such binaries. Newtonian simulations give an insufficient neutrino luminosity to power a GRB (Ruffert, Janka & Schäfer 1996) while general relativistic calculations indicate no blast wave will be formed, although a GRB with a smooth time profile is the computed outcome (Wilson, Mathews & Maronetti 1996, Wilson 1997).

It has been proposed (Paczyński 1991) that in the binary coalescence of a neutron star with a black hole the star would be disrupted into a torus which would accrete on the viscous timescale, thus extending the duration of the burst. Our simulations show a rather different outcome, but it remains true that the process is extended in time (for a different reason). Theoretical estimates (Lattimer & Schramm 1976, Narayan, Piran & Shemi 1991) give $\sim 10^{-6}$ per year per galaxy for the rate of coalescence of such binaries, in agreement with the observed rate of GRBs. The energy release is comparable to that in the double neutron star mergers. Thus, the process seems to share all the advantages of the coalescing neutron stars scenario, while avoiding its main shortcomings. This motivated our study.

3. Numerical Method

For the computations presented in this letter, we have used a fully Newtonian smooth particle hydrodynamics (SPH) code (Lucy 1977, Gingold & Monaghan 1977). A detailed description of the code will be published elsewhere (Lee & Kluźniak 1997b). In calibration runs of the code, we have replicated (Lee & Kluźniak 1995) in detail all features of the binary neutron star mergers computed by Rasio & Shapiro (1994). The neutron star was modeled as a polytrope with a stiff equation of state (adiabatic index $\Gamma = 3$) with 17,000 particles. The black hole was modeled as a point mass with an absorbing boundary at $r_g = 2GM/c^2$. Any particle that comes closer than r_g to the black hole is absorbed, the mass and momentum of the black hole are adjusted so the that total mass and linear momentum are conserved. The detailed results presented here were obtained for initial conditions corresponding to a tidally locked neutron star. Initial synchronized equilibrium configurations can be constructed via a relaxation technique for a range of binary separations, allowing the polytrope to respond to the presence of the tidal field (Rasio & Shapiro 1992). During the dynamical coalescence, we also calculate the gravitational radiation waveforms emmitted by the system, in the quadrupole approximation. These waveforms are presented elsewhere (Lee & Kluźniak 1997a,b).

4. Results and Discussion

In the coalescence, the two components of the binary are brought together by the loss of angular momentum to gravitational radiation. A particularly interesting case occurs when the mass of the black hole is close to that of the neutron star. In this case a dynamical instability appears, and the orbit decays on a dynamical timescale. The results of model calculations with an initial mass of the neutron star of 1.4 $M_\odot$ and unperturbed radius of the polytrope of 13.4 km are presented in Figures 1 and 2. Upon relaxing the polytrope to a synchronized state in the binary system, we find the onset of instability at a distance of 37 km, this is the initial binary separation in the simulation presented in Figures 1 and 2.

Figure 2 shows density contour snapshots during a dynamical simulation with an initial mass ratio of one ($q = 1$). A transient massive accretion torus forms around the black hole, but the neutron star is not completely disrupted as a result of this encounter. To the limit of our resolution ($10^{-4}M_\odot$), a baryon–free line of sight, parallel to the rotation axis of the binary, remains present throughout the simulation. Higher resolution runs are needed to determine whether the baryon content is below $10^{-5}M_\odot$, as required by the blast–wave model of GRBs (Mészáros & Rees 1993). The total energy released through viscous heating is $\approx 5 \times 10^{52}$ erg. In this case, mass transfer is essentially over in approximately five initial orbital periods (11 ms) and a remnant core containing 0.43 $M_\odot$ is left orbiting around a 2.25 $M_\odot$ black hole.

In Figure 1 we have plotted (solid line) the mass accretion rate onto the black hole, showing that the accretion event is very brief ~ 2 ms; the dashed line is the mass of the black hole as a function of time. The configuration resulting from the unstable mass transfer in a binary of initial mass ratio $q = 1$ is that of a black hole and a lighter remnant core left in orbit of greater separation (~ 60 km) and a greatly altered mass ratio ($q_{final} = 0.19$). The orbital separation in this new binary system will again decrease due to continuing emission of gravitational waves and, after ~ 0.1 s, Roche-lobe overflow will occur as described below. In the initial mass transfer for $q = 1$, the black hole was a messy eater and $\sim 0.1M_\odot$ of mass from the original neutron star remains scattered around the binary system. With the current resolution of our computations we were unable to determine the exact distribution of this matter after 0.1 s. It is possible that some of this matter will eventually be accreted onto the black hole, potentially releasing up to 10^{51} erg in energy. We expect that much of the remaining neutron matter will release its nuclear binding energy on the beta decay timescale ($\tau \approx 15$ minutes).

For mass ratios not too close to unity ($q \equiv M_{ns}/M_{BH} < 0.8$), we find no dynamical instability. Once the components are brought sufficiently close an episode of mass transfer through Roche–lobe overflow from the neutron star onto the black hole ensues. This causes

the neutron star to move away from the black hole (by conservation of angular momentum). The event is "clean," all the mass lost by the neutron star is accreted by the black hole. These results are quite different from those of early estimates, which suggested that the neutron star will be tidally disrupted (Wheeler 1971, Lattimer & Schramm 1976) and that a few per cent of the mass will be ejected (Lattimer & Schramm 1976) to infinity, although it should be noted that our calculations are completely Newtonian. If gravitational radiation backreaction is neglected, the peak accretion rate is about $2M_\odot$/s, but only about one percent of the neutron star mass is transferred in each episode.

The accretion rate and the mass transferred in such an episode are illustrated in Figure 3, for a $1.4M_\odot$ neutron star orbiting a $4.5M_\odot$ black hole ($q = 0.31$). Here, the critical distance corresponding to Roche–lobe overflow is 50.4 km. After an interval of time comparable with the duration of the accretion event, $\sim 4\,$ms, gravitational radiation again forces the binary into a configuration where mass transfer occurs again. Clearly, the number of such accretion events would be $\sim M_{ns}/\Delta M_{BH} \sim 100$ and the total duration of the process a few seconds. However, gravitational radiation losses cannot be ignored in this case, since the time scale for decay for the orbit (from angular momentum losses to gravitational waves) in the point mass approximation is 3.5 ms and the duration of the mass transfer episode presented in Figure 3 is 10 ms. To explore how these angular momentum losses to gravitational radiation will affect the binary, we have calculated, using the quadrupole approximation for angular momentum loss, the evolution of the same binary assuming that the gravitational potential is that of two point masses. After 10 ms of mass transfer, the binary separation has increased by about 0.06% and the mass of the neutron star is 0.85 $M_\odot$. Thus, this approximation also leads to the conclusion that the binary will survive with an altered mass ratio and separation, and the total time scale of the coalescence process is extended from a few milliseconds to at least several tens of milliseconds. Full hydrodynamical simulations involving a backreaction force are required to explore the evolution of such a binary in greater detail.

Note that we have identified the final stages of evolution of the black-hole neutron-star binary as the only known astrophysical process leading to the creation of a low-mass neutron star. The coalescence ends with an explosion (Colpi, Shapiro & Teukolsky 1991, Sumiyoshi *et al.* 1997) when the mass of the surviving core drops below the lower stability limit of neutron stars. This in itself could also give rise to an observable transient. As pointed out by the referee, the black hole member of the binary will be left behind with a large linear velocity as a result of the explosion and the associated recoil. Our simulations suggest a velocity on the order of 10^4 km/s.

In summary, we have identified several unexpected features in the binary coalescence

of a neutron star with a black hole, which may make such events promising candidate sources for the central engine of gamma-ray bursters, at least for the shorter bursts in the apparently bimodal distribution (Kouveliotou *et al.* 1995). The Newtonian numerical calculations presented here assumed that the rotation of the neutron star was synchronized with the orbital period. In fact, tidal locking is not expected (Bildsten & Cutler 1992). Our preliminary simulations for a non–synchronized system with an initial mass ratio of $q = 0.31$ show that the core of the neutron star survives the initial mass transfer episode and could be driven below the minimum mass required for stability. Thus the outcome is similar to that for the tidally locked binary. Finally, all of our results are predicated on the assumption that the neutron star will not collapse to a black hole before the onset of mass transfer, relativistic simulations are required to address the validity of this assumption (Wilson, Mathews & Maronetti 1996).

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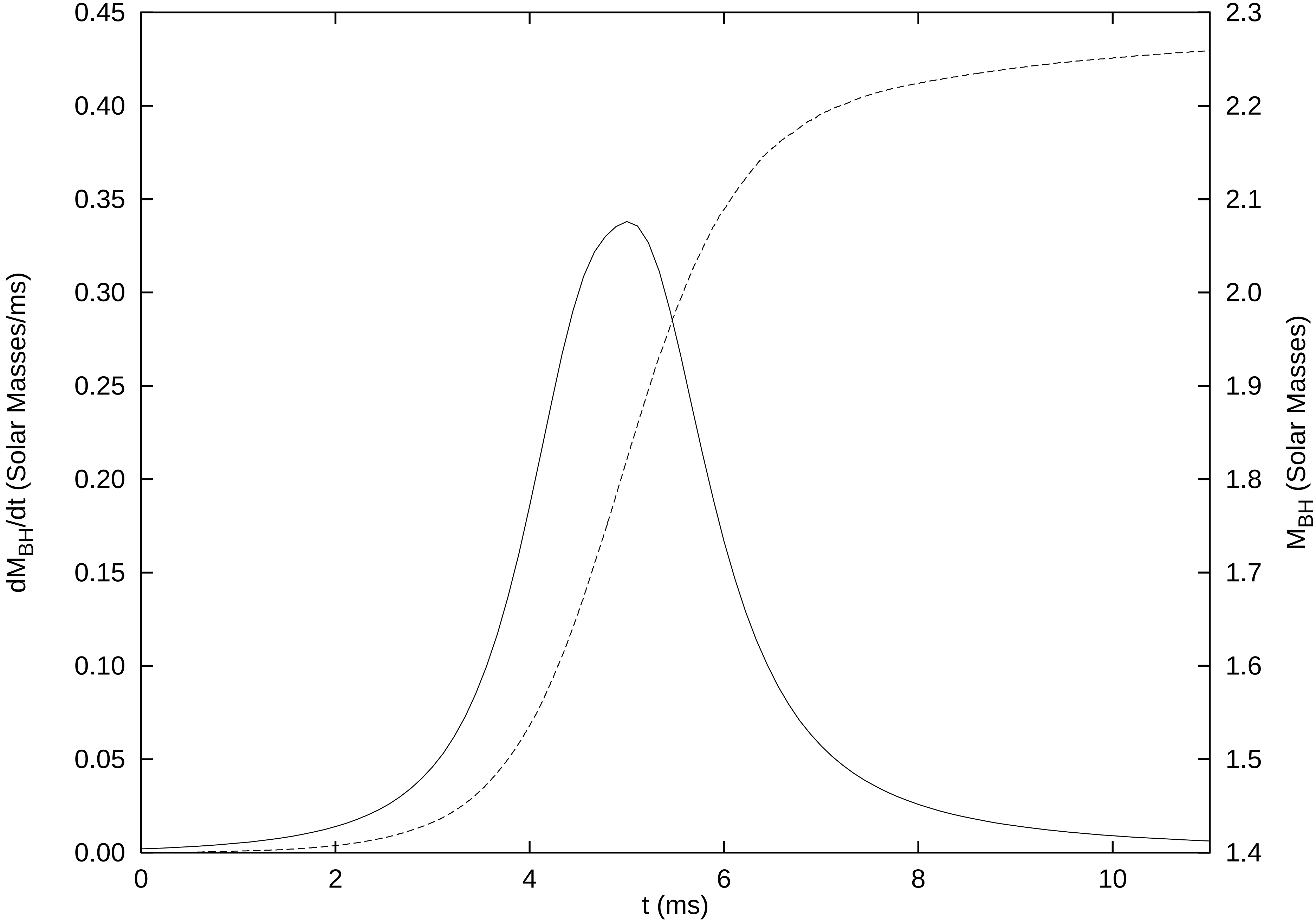
Fig. 1.— Black hole mass (dashed line) and mass accretion rate onto the black hole (solid line) for an initial mass ratio of q=1.

Fig. 2.— Density contours at various times during the dynamical coalescence of the black hole–neutron star binary with an initial mass ratio q=1 and initial separation r=37 km. The color–coded density ranges from 5×10^{17} kg m^{-3} (bright yellow) to 5×10^{14} kg m^{-3} (dark blue), and the box shown is 161 km on a side. The rotation is about the z–axis and counterclockwise in a) and b); the initial orbital period is P=2.3 ms. Density contours in the orbital plane are shown at: a) t=4.6 ms and b) t=6.9 ms. Contours in the meridional plane are shown at: c) t=6.9 ms and d) t=9.2 ms. The baryon–free axis and the transient accretion torus are clearly seen. The black disk represents the black hole.

Fig. 3.— The change in black hole mass (dashed line) and mass accretion rate onto the black hole (solid line) for an initial mass ratio of q=0.31. The turn–off of the mass transfer may be related to the absence of gravitational radiation reaction in our simulation.



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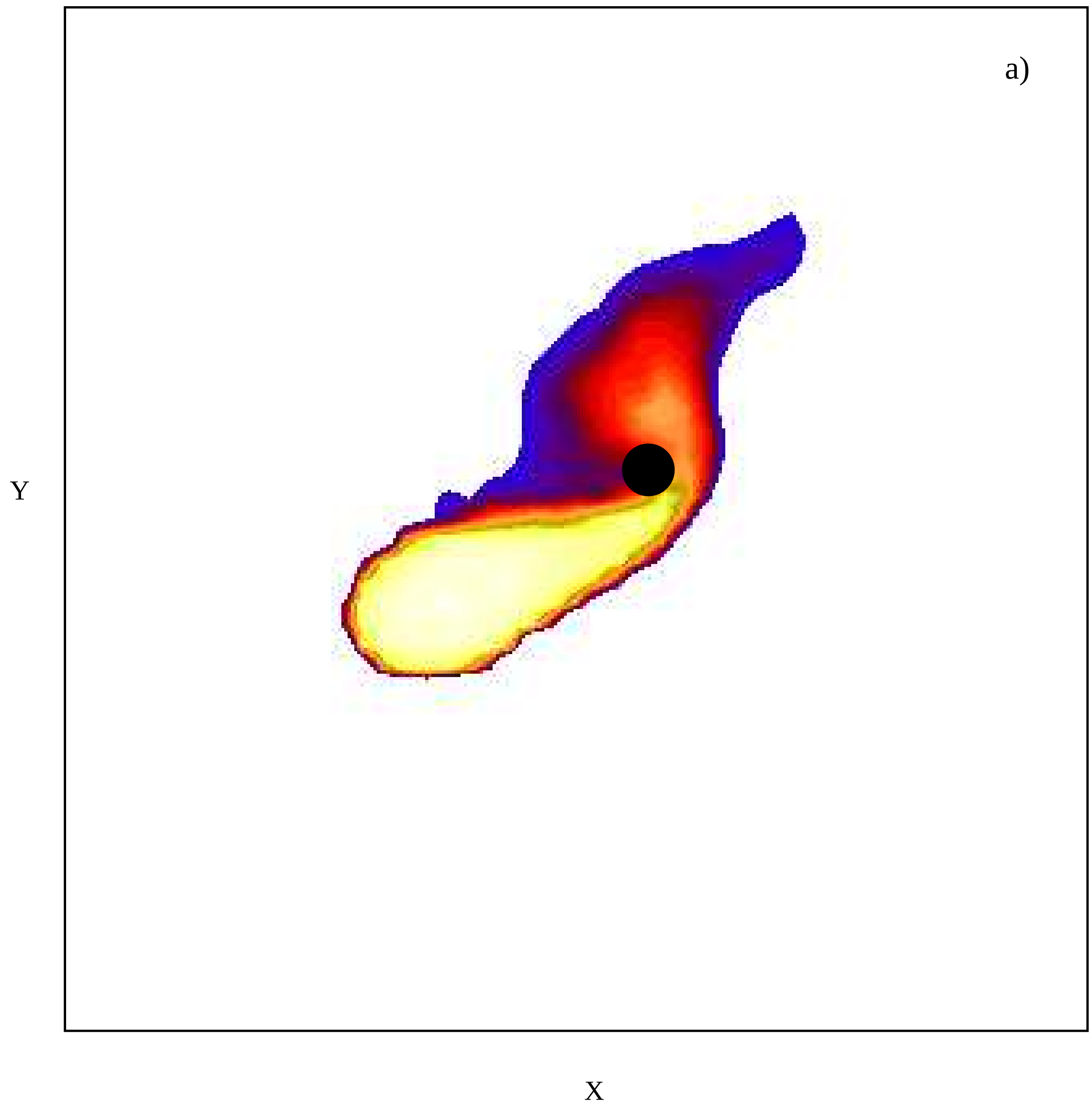
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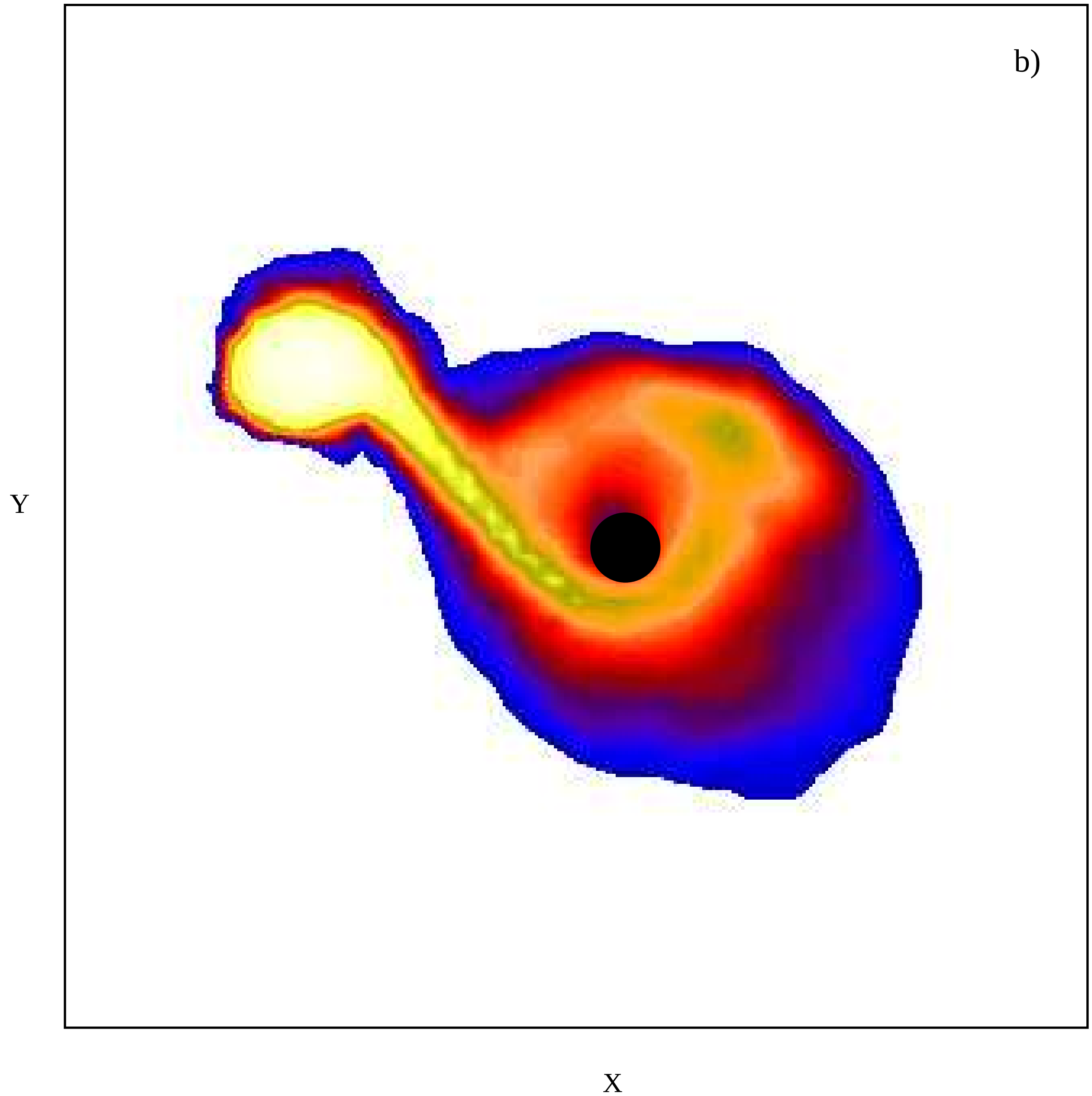

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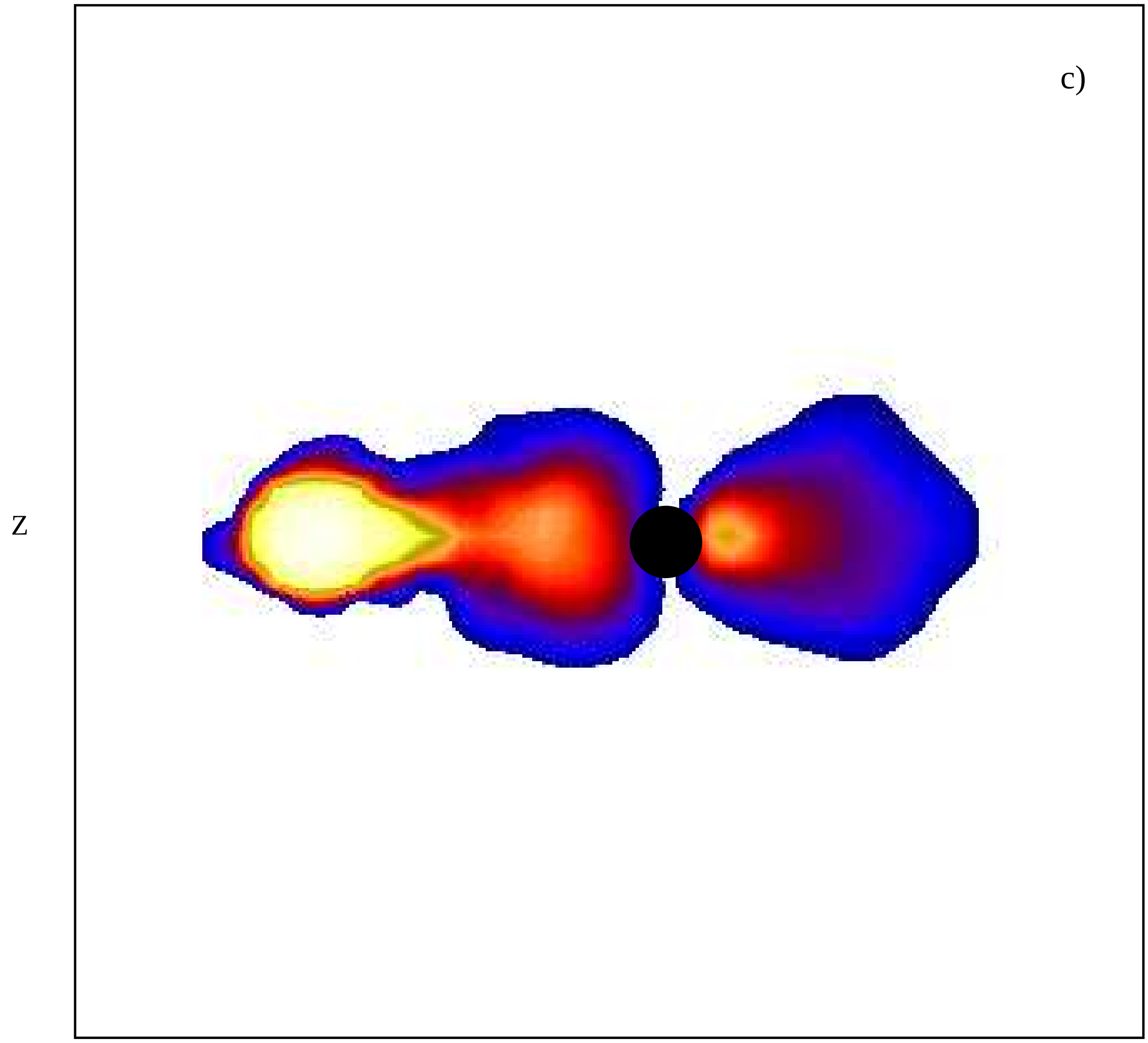
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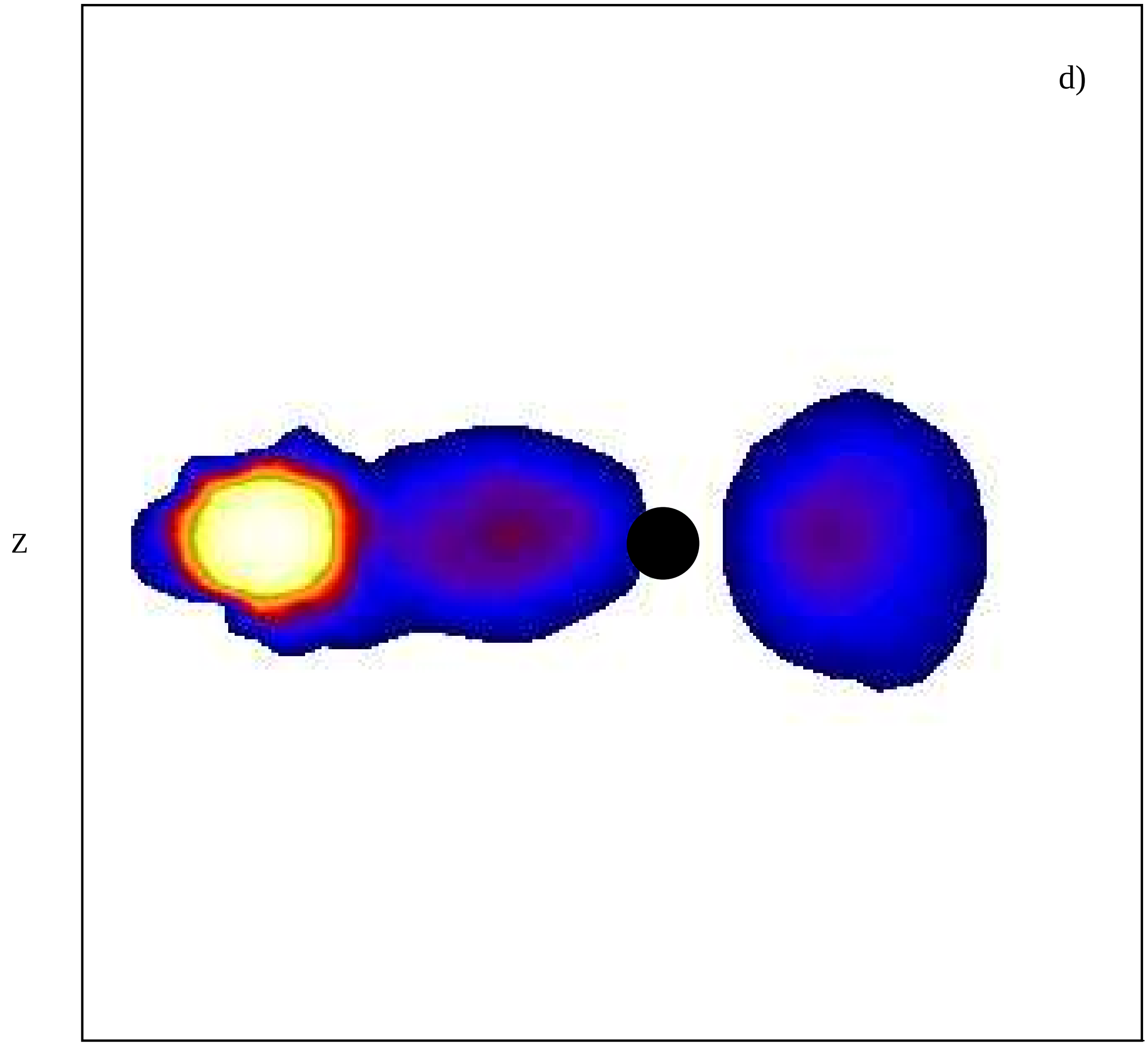
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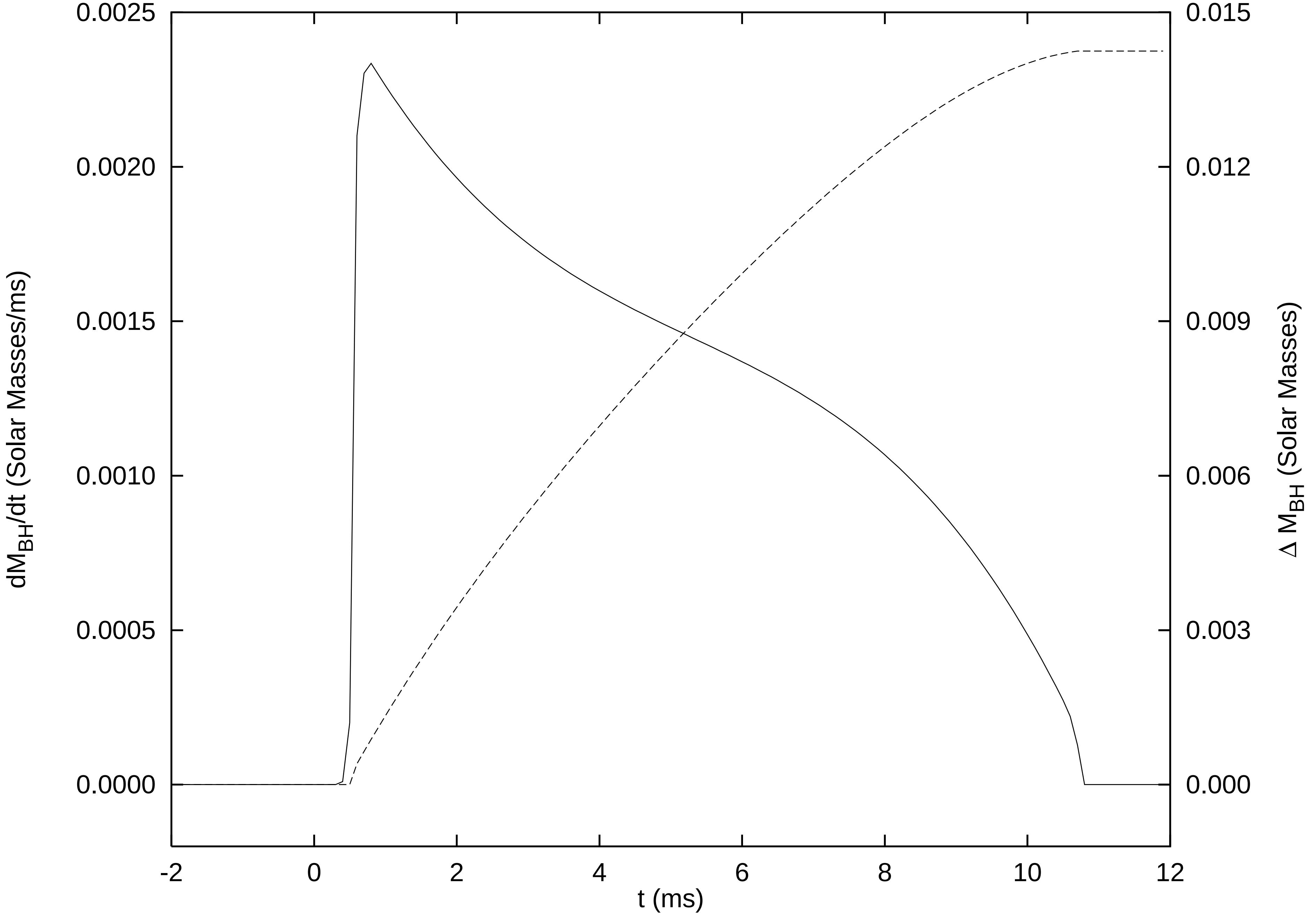

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